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Procedia Materials Science 3 (2014) 706 – 713
Procedia Materials Science
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20th European Conference on Fracture (ECF20)

Limit load solutions of V-groove welded pipes with a circumferential crack at the centre of weld

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Abstract

The accurate estimation of limit loads are important for defect assessment and are strongly related with strength mismatch and weld geometry. Previous closed form solutions of mis-match limit loads were proposed by J-S Kim et al. (2009), for idealized butt weld configuration and are a function of the strength mis-match ratio with only one geometry-related slenderness parameter. Present work reports mis-match limit loads for V-groove welded pipe for a circumferential crack via detailed 2D and 3D FE analysis. Fully-circumferential surface crack and part-through surface crack are considered and are located at the centre of the welds with various groove angles. With regards to loading condition, axial (longitudinal) tension is applied for all cases. For the parent and weld metal, elastic-perfectly plastic materials are varied systemically to analyze under-matching and over-matching conditions in plasticity. To integrate the effect of groove angles on mis-match limit loads, one geometry-related slenderness parameter was modified by relevant geometric parameters including groove angle, crack depth, crack width and root opening, based on plastic deformation patterns in theory of plasticity.

Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering

Keywords: Mismatch Limit load, Circumferential Crack, V-groove, Weldment

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doi:10.1016/j.mspro.2014.06.116

1. Introduction

The accurate estimation of limit loads are important for defect assessment and are strongly related with strength mismatch and weld geometry. There were various mis-match limit load solutions recommended for different cracked

Nomenclature

a	crack depth
E	Young's modulus
h	half width of weld metal strip, root opening
h_{eff}	modified width of weld
M_F	mismatch factor defined for yield strength, MF = σ_{YW} / σ_{YB}
N, N_L	axial tension and limit tension
r	pipe radius
t	pipe thickness
θ	half of circumferential angle of crack
ϕ	groove angle
σ_y	limit strength of an elastic-perfectly plastic material
σ_{YB}	limit strength of base material
σ_{YM}	limit strength of an weld material
ψ	Parameter related to slenderness of the weld
ψ_{eff}	modified Parameter related to slenderness of the weld
Subscripts	
B	referring to base metal
M	referring to mis-match configuration
W	referring to weld metal

geometry through defect assessment procedures such as R6 code. One of the most important finding is that mis-match limit loads can be quantified by two parameters; the strength mis-match ratio and the parameter related to the slenderness of the weld. In addition, significant effects of the slenderness parameter are emphasized on mis-match limit loads

Extensive results are reported from the mismatch limit load, but most of the published works are limited to idealize two-dimensional and axisymmetric geometries. For such ideal cases, the parameter related to the slenderness of the weld can be easily defined as the ratio of the remaining ligament to the half weld width. More recently, the authors presented strength mis-match effect on limit loads for circumferential surface cracked pipes in the centre of the weld metal by by J-S Kim et al. (2009). It was found that, even for part-through surface cracks, mis-match limit loads could be characterized by the strength mis-match ratio and one of the parameter related to the weld slenderness. This is fairly a significant result in the sense that one parameter associated with the slenderness of the weld is adequate to quantify mis-match limit loads even for part-through surface cracks. The latest work of J-S Kim et al. (2009), the weldment is assumed as an idealized geometry (simple strip) but in actual conditions, it is not. The present work provides mis-match limit loads for V-groove butt-welded pipes with circumferential surface crack in the centre of the weld. Based on systematic FE limit analyses, effects of mis-match related variables on mis-match limit loads for pipes with circumferential surface cracks are quantified.

2. Finite element limit analysis

2.1. Geometry and analysis matrix

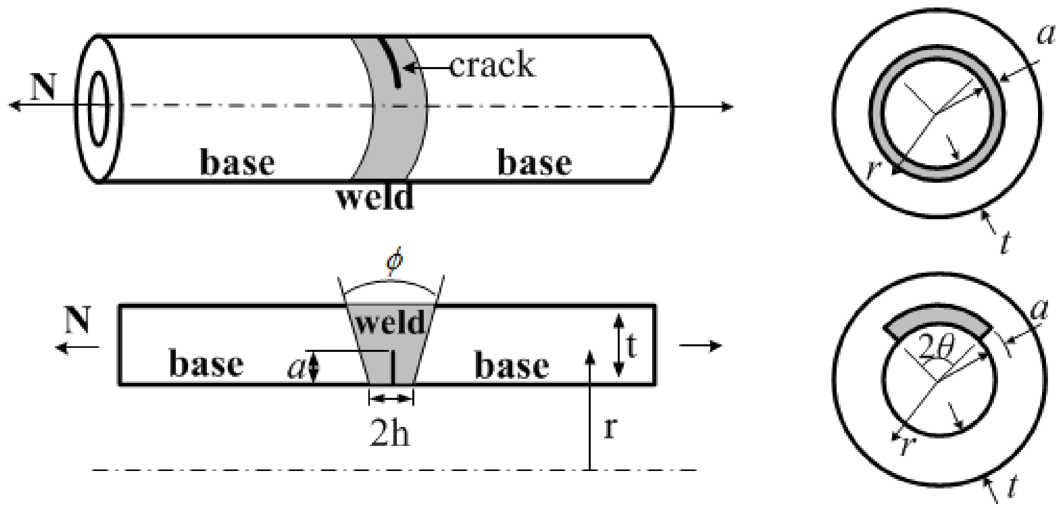


Fig. 1 Schematic illustrations of circumferential cracked pipes under tension N: Fully circumferential surface crack and part through surface crack

Figure 1 depicts butt-welded pipes with circumferential surface cracks including fully circumferential surface cracked pipe and part through surface crack, considered in the present work. Referring to the previous work done by J-S Kim et al. (2009), the analysis was concentrated on an idealized butt weld configuration (a simple strip model where the weld metal strip has a rectangular cross section), and a crack is assumed to be located in the centre of the weld. But as for present work, the weld configuration in Fig.1 was used considering a different weld configuration of V-groove butt weld. The pipe is characterized by its mean radius, r, and thickness, t. The root opening of the weld has the width of $2h$. The groove angle of the weld is defined as ϕ. The surface crack is characterized by its circumferential angle, 2θ, and depth, a in Fig. 1. Appropriate variables possibly affecting limit loads are systematically varied in the present work but low depth cracks ($a/t < 0.5$) are not concerned which causes gross section yielding (Table.1). Two different values for r/t are considered as $r/t = 5$, 20 and values of θ/π are systematically varied. For the weld width ratio, two values of h/t are used ($h/t = 0.125$, 0.2) because of its small values of real structure. Finally two different values of M_F ($M_F = 0.5$, 2.0) are considered which of limiting cases of latest work done by J-S Kim et al. (2009).

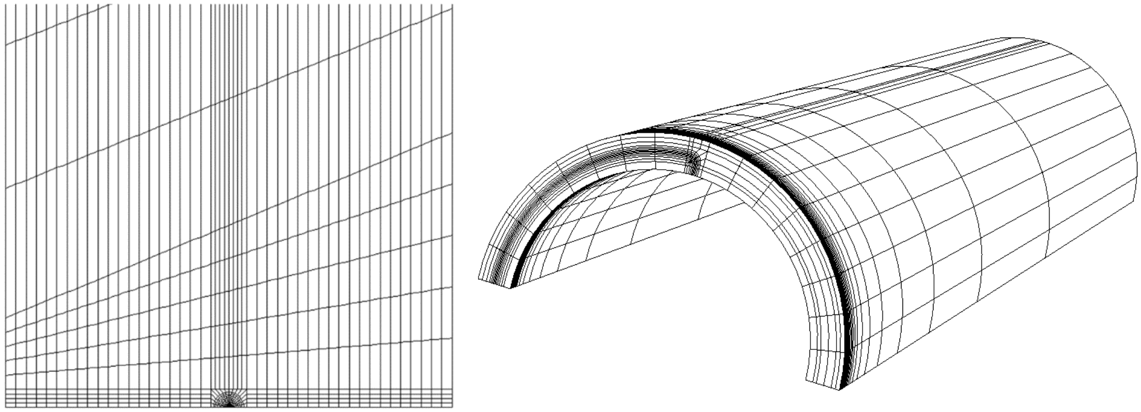
Figure 2 represents typical FE meshes for pipes with fully circumferential surface cracks and part through surface cracks which used in the present work. To reduce the computing time, symmetry conditions are applied in the FE models and 20-node iso-parametric quadratic brick elements with reduced integrations (C3D20R within commercial program ABAQUS) are used for part through surface crack and 8-node axisymmetric elements with reduced integrations (CAX8R within commercial program ABAQUS) are used for fully circumferential surface crack. Concerning loading conditions, axial tension is considered for all cases.

2.2. FE limit analysis.

Elastic-perfectly plastic analyses of FE models were performed using ABAQUS. Materials are assumed as elastic perfectly plastic and non-hardening is used with relations to a small geometry change continuum FE model. The MPC (multi-point constraint) options are used for apply loading within ABAQUS.

Table 1. Analysis parameters considered in this work.

r/t	h/t	a/t	ϕ	θ/π
5 20	0.125 0.2	0.5 0.6 0.8	20° 45° 70° 90°	0.25 0.5 0.8



(a) (b)

Fig. 2. (a) Typical FE meshes for fully circumferential surface cracked pipe; (b) Typical FE meshes for part through circumferential surface crack

3. Mis-match limit loads.

3.1. surface cracks on idealized butt weld

An idealized butt weld configuration was considered in the previous works by J-S Kim et al. (2009). The mis-match in the yield strength between the weld metal, σ_{YW}, and the base plate, σ_{YB}, is quantified by the mismatch factor M_F:

$$M_F = \sigma_{YW} / \sigma_{YB} \quad (1)$$

with M_F <1 referring to under-matching and M_F >1 referring to over-matching. Another important mis-match related parameter is the slenderness of the weld. For the Fully circumferential surface cracked pipe, it is defined as

$$\psi = \frac{(t-a)}{h} \quad (2)$$

For the part through circumferential surface cracked pipe, it is defined as

$$\psi = \frac{(t-a)}{h} + 5\left[\cos\left(\frac{\theta}{2}\right) - \frac{\sin\theta}{2}\right] \quad (3)$$

2θ and $2h$ denote the circumferential angle of crack and weld width. Mismatch limit load solutions for fully circumferential surface cracked pipe and part through surface cracked pipe on tension with cracks in the center of the weld, are briefly summarized here. N_{LB} is the limit load for the surface cracked pipes made totally by the base metal and N_{LM} is the mis-match limit load for the pipes.

For over-matching, limit load solutions are given by

$$\frac{\mathrm{N_{LM}}}{\mathrm{N_{LB}}}=\begin{cases}\min\left(M_F,\dfrac{1}{n_{LB}}\right) & \mathit{for}\quad 0\le\psi\le\psi_1\\ \min\left(\dfrac{24(M_F-1)}{25}\left(\dfrac{\psi_1}{\psi}\right)+\dfrac{(M_F+24)}{25},\ \dfrac{1}{n_{LB}}\right) & \mathit{for}\quad \psi_1\le\psi\end{cases}\qquad \psi_1=\exp\left[-\frac{2(M_F-1)}{5}\right]\tag{4}$$

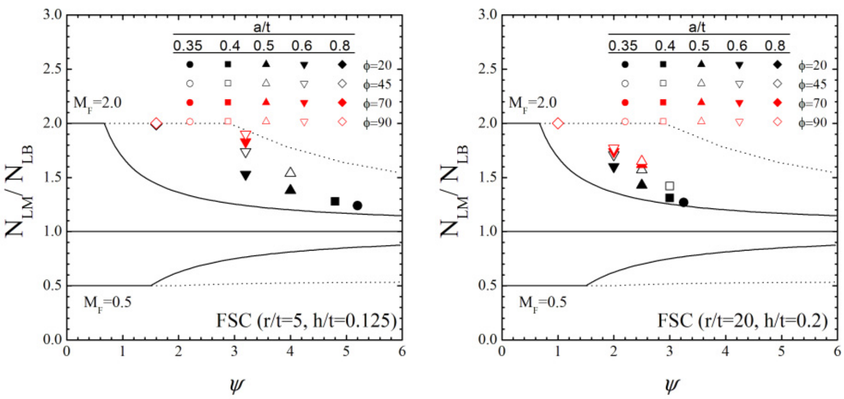
For under-matching,

$$\frac{\mathrm{N_{LM}}}{\mathrm{N_{LB}}}=\begin{cases}M_F & \mathit{for}\quad 0\le\psi\le 1.5\\ 1-\dfrac{1.5(1-M_F)}{\psi} & \mathit{for}\quad 1.5\le\psi\end{cases}\tag{5}$$

The results of limit load solution for idealize butt weld provides that mismatch limit loads can be characterized by two parameters, M_F and ψ. But with V-groove weld, the limit load solution doesn't provide good agreement with FE results of V-groove pipes because of changes of weld geometry. Fig.3 show the variations of FE results for V-groove fully circumferential surface cracked pipes and exhibits the differences caused by groove angle changes. According to geometrical change of welds, it is necessary to revise the limit load solution.

Considering the effect of the groove angle the effective weld width of the weld is defined as average of uncracked weld ligament and the equation of effective weld width is modified by FE results. Effective weld width is defined as:

$$\begin{aligned} h_{\mathrm{eff}} &= \bar{h}-\frac{t}{2}\sin(\phi)\tan(\phi/2) && \mathit{form}.1\\ h_{\mathrm{eff}} &= h+\frac{(a+t(1-\sin\phi))}{2}\tan(\phi/2) && \mathit{form}.2\end{aligned}\tag{6}$$



(a) (b)

Fig. 3. Variations of normalized FE mis-match limit loads N_{LM}/N_{LB} for fully circumferential surface cracked pipes for V-groove welds with *h*.; (a)r/t= 5, h/t 0.125, (b) r/t = 20, h/t 0.2

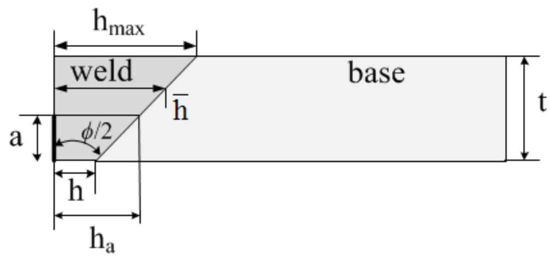


Fig. 4. Schematic illustration of circumferential surface crack: $\bar{h}$ (average width of uncracked weld ligament)

3.2. Fully circumferential surface crack on V-groove butt weld

FE limit loads results for mis-matched pipes with fully circumferential surface cracks, for two different values of h/t =0.125, 0.5 and for various values of ϕ are presented. Fig. 5 show that FE results agree well with suggested solutions (Eq. 4~6) for various groove angle and crack depth for both of thick and thin pipes.

The results in Fig.5 show that thick wall pipes (r/t =5) and thick weld (h/t = 0.2) cause gross section yielding on low a/t (a/t = 0.5) which are not concerned. For under-matching FE results gives normalized mis-match limit loads (N_{LM}/N_{LB}) are same value of strength mis-match ratio (M_F = 0.5) for large groove angle results($\phi \geqq 45°$).

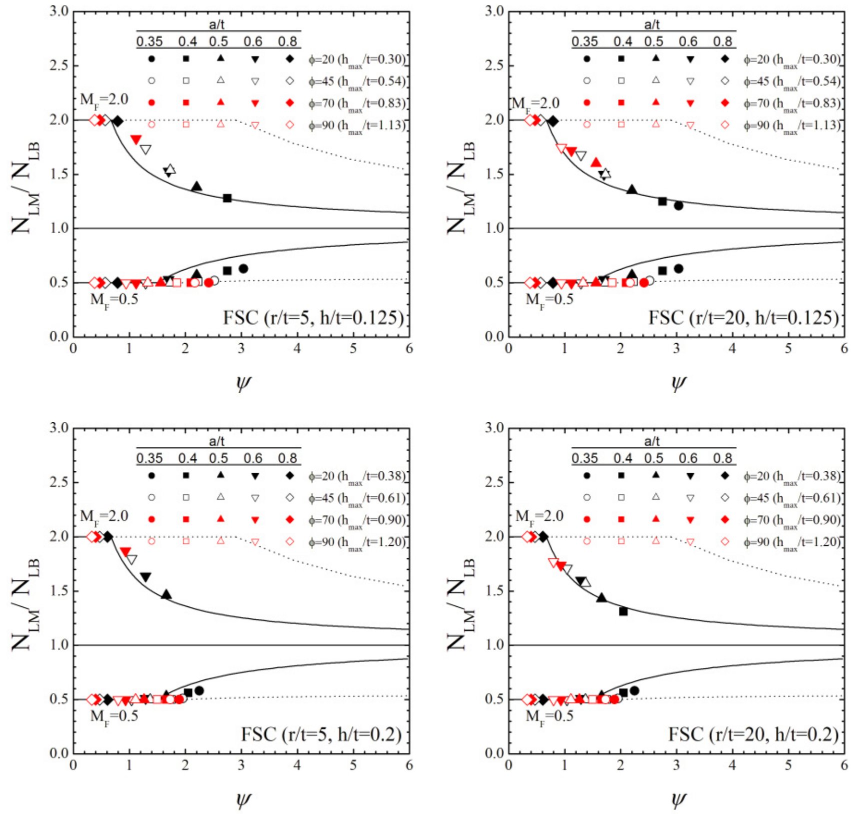


Fig. 5. Variations of normalized FE mis-match limit loads N_{LM}/N_{LB} for fully circumferential surface cracked pipes with h_{eff}.

3.3. Part through surface crack on V-groove butt weld

FE limit loads results for mis-matched pipes with part through surface cracks are also agree well with suggested solution for various values of ϕ. Fig. 6 show that FE results for various groove angle and crack depth. The results in Fig.6 also shows that thick wall pipes (r/t =5) and thick weld (h/t = 0.2) cause gross section yielding on low a/t (a/t = 0.5) which are not concerned. For under-matching FE results show that normalized mis-match limit loads are lies along the M_F =0.5 line for large groove angle. The results with small groove angles are bit larger than M_F but gives conservative results.

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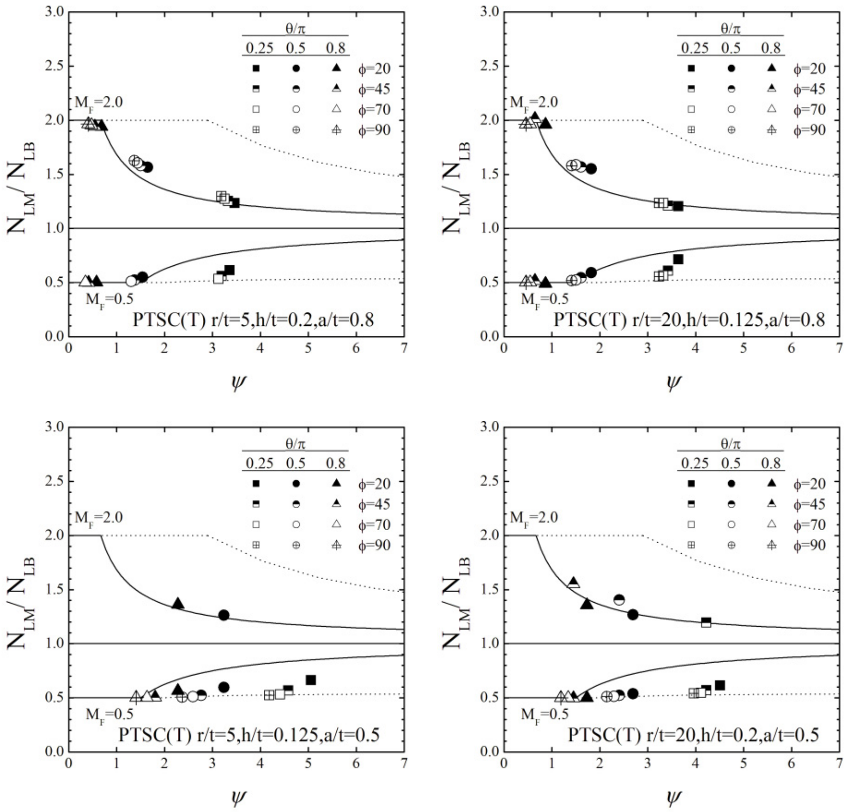

Fig. 6. Variations of normalized FE mis-match limit loads N_{LM}/N_{LB} for part through surface cracked pipes with h_{eff}.

4. Conclusions.

The present work provides mis-match limit loads for welded pipes with circumferential surface cracks in the centre of the weld. Based on systematic three-dimensional FE limit analyses, the effects of mis-match related variables on plastic limit loads are quantified by two parameters; the strength mis-match ratio and the parameter related to the slenderness of the weld considering the effect of groove angle. It should be noted that similar analyses are being performed for idealized butt weld pipe in tension to lead similar conclusions. Based on FE results, a form of geometry-related parameter which considered of groove angle be proposed. To integrate the effect of groove angles on mis-match limit loads, one geometry-related slenderness parameter was modified by relevant geometric parameters including groove angle, crack depth, crack width and root opening, based on plastic deformation patterns in theory of plasticity.

Acknowledgements

This research was supported by Engineering Research Center Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Science, ICT and Future Planning. (NRF-2007-0056094)

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